SCENARIO ANALYSIS FOR THE SAN PEDRO RIVER, ANALYZING HYDROLOGICAL CONSEQUENCES OF A FUTURE ENVIRONMENT

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Abstract. Studies of future management and policy options based on different assumptions provide a mechanism to examine possible outcomes and especially their likely benefits and consequences. The San Pedro River in Arizona and Sonora, Mexico is an area that has undergone rapid changes in land use and cover, and subsequently is facing keen environmental crises related to water resources. It is the location of a number of studies that have dealt with change analysis, watershed condition, and most recently, alternative futures analysis. The previous work has dealt primarily with resources of habitat, visual quality, and groundwater related to urban development patterns and preferences. In the present study, previously defined future scenarios, in the form of land-use/land-cover grids, were examined relative to their impact on surface-water conditions (e.g., surface runoff and sediment yield). These hydrological outputs were estimated for the baseline year of 2000 and predicted twenty years in the future as a demonstration of how new geographic information system-based hydrologic modeling tools can be used to evaluate the spatial impacts of urban growth patterns on surface-water hydrology.

Keywords: alternative futures analysis, hydrologic modeling, watershed assessment, geographic information systems, landscape indicators, landscape characterization, remote sensing, regional vulnerability, San Pedro River

1. Introduction

The assessment of land use and land cover is an extremely important activity for contemporary land management. A large body of literature (e.g., Houghton et al., 1983; Turner, 1990; McDonnell and Pickett, 1993) suggests that human land-use practices (including type, magnitude, and distribution) are the most important factors influencing natural resource management at local, regional, and global scales.

Today's environmental managers, urban planners, and decision-makers are increasingly expected to examine environmental and economic problems in a larger geographic context. To accomplish this, it is necessary to 1) understand the scale at which specific management actions are needed; 2) conceptualize environmental management strategies; 3) formulate sets of alternatives to reduce environmental and economic vulnerability and

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uncertainty in their evaluation analyses; and 4) to prioritize, conserve, or restore valued natural resources, especially those which provide important economic goods and services.

A scenario-based approach to regional land planning offers an organizational basis to explore decision analysis and opportunities for public resources. Scenario planning was initially used by the military after the Second World War and has since been tested in a variety of geographical settings to assist stakeholders and policy makers in shaping future use of land and water resources (Schwartz, 1996; Steinitz, 1990).

Compared with other assessment frameworks, scenario analysis offers several advantages, including the ability to intentionally investigate several "futures" or different points of view at one time. The most important reasons for employing scenario analysis relate primarily to the potential benefits of evaluating all aspects of the local decision-making processes. For example, for land owners interested in protecting their property rights, scenario analysis can be used to understand the range of potential impacts to their lands that may be caused by regional change relative to the type, location, and magnitude of proposed management actions or policy. Additionally, for elected officials and public administrators, scenarios can be used to test current planning ideas in terms of public perceptions or presumed demographic changes. Thus, scenarios can be used to test the resilience of plans against assumptions about the stability and growth into the future. Lastly, the use of scenarios allows members of an entire community to assess the relative impacts of several alternative sets of choices for a desirable future environment. Scenario analysis thus requires that scenarios be possible, credible, and relevant to be useful in decision-making processes.

This paper presents the results of a study that examines the impact of urban development in a semi-arid environment relative to sustainability of water resources, its most crucial asset. In particular, it attempts to answer questions that relate to future scenarios that describe extremes in position (e.g., development options that are most development and least conservation oriented and vice versa) with the idea that urban growth patterns can be managed to minimize hydrologic and environmental impacts.

2. Materials and Methods

Landscape architecture involves several areas of theory, all of which influence design. Much of the contemporary thinking in regard to landscape design analysis has been outlined in various studies performed at the Harvard University Graduate School of Design (Steinitz et al., 2003, 2000, 1996, 1993, 1990). In these studies potential impacts from a number of wide-ranging scenarios are compared to current conditions of a region in terms of a set of processes that are modeled in a geographic information system (GIS). Alternative future landscape analysis involves describing the patterns and significant human and natural processes affecting a geographic area of concern, constructing GIS models to simulate these processes and patterns, creating changes in the landscape by forecasting and by design, and evaluating how the changes affect pattern and process using models (USEPA, 2000).

The application of several advanced technologies to assess the hydrological consequences of future human development in a moderately-sized southwestern watershed is described below. The primary source data were three land-cover/land-use grids representing alternative futures for the San Pedro River Basin in the year 2020. These data were derived from a study of changing landscape patterns, in which they were compared to a baseline year of 2000 for the purpose of assessing groundwater and biological impacts (Steinitz et al., 2003; Kepner et al., 2002). The case study area was selected for a variety of reasons including data richness and stakeholder involvement.

The Upper San Pedro River Basin originates in Sonora, Mexico and flows north into southeastern Arizona (Figure 1). The Upper San Pedro watershed represents a transition area between the Sonoran and Chihuahuan deserts. Topography, climate, and vegetation vary substantially across the watershed (Tellman et al., 1997; CEC, 1998). Elevations range over 900–2,900 m and annual rainfall ranges from 300 to 750 mm. Biome types include desert scrub, grasslands, oak woodland-savannah, mesquite woodland, riparian forest, coniferous forest, and agriculture (Kepner et al., 2000). The upper watershed encompasses an area of approximately 7,600 km^2 (5,800 km^2 in Arizona and 1,800 km^2 in Sonora, Mexico) and is the only unimpounded river in Arizona. All municipal and most agricultural water is derived from groundwater sources.

The Automated Geospatial Watershed Assessment (AGWA) tool (Miller et al., 2002; *http://www.epa.gov/nerlesd1/land-sci/agwa/index.htm; http://www.tucson.ars.ag.gov/agwa/*) is a multipurpose hydrologic analysis system for use by watershed, natural resource, and land-use managers and scientists in performing watershed- and basin-scale

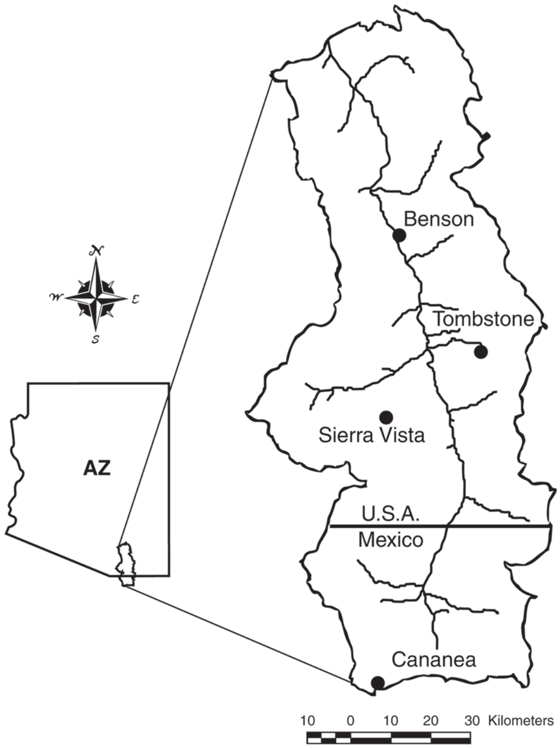

Figure 1. Location of the Upper San Pedro River Basin, Arizona/Sonora.

studies. It was used in this study to evaluate the relative hydrologic consequences of anticipated future urban and suburban development.

AGWA is an extension for the Environmental Systems Research Institute's (ESRI) ArcView versions 3.X (ESRI, 2001), a widely used and relatively inexpensive Personal Computer (PC)-based GIS software package. The GIS framework is ideally suited for watershed-based analysis, which relies heavily on landscape information for both deriving model inputs and presenting model results. In addition, AGWA shares the same ArcView GIS framework as the U.S. Environmental Protection Agency (U.S. EPA) Analytical Tool Interface for Landscape Assessment (ATtILA) (Ebert and Wade, 2000), and Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) (Lahlou et al., 1998). This facilitates comparative analyses of the results from multiple environmental assessments, thus making it particularly valuable for interdisciplinary studies, scenario development, and alternative futures simulation work (Hernandez et al., 2003).

AGWA is designed to support landscape assessment at multiple spatial and temporal scales and provides the functionality to conduct all phases of a watershed assessment for two widely used watershed hydrologic models: the Soil Water Assessment Tool (SWAT) (Arnold et al., 1994); and a customized version of the KINematic Runoff and EROSion Model (KINEROS2) (Smith et al., 1995). SWAT is a continuous simulation model for use in large (river-basin scale) watersheds. KINEROS2 is an event-driven model designed for small arid, semi-arid, and urban watersheds. Data requirements for both models include elevation, land cover, soils, and precipitation data. Model input parameters are derived directly from these data using optimized look-up tables that are provided with the tool.

The tasks necessary to conduct a watershed assessment can be broken out into five major steps: 1) location identification and watershed delineation; 2) watershed subdivision 3) land cover and soils parameterization; 4) preparation of parameter and rainfall input files; and 5) model execution and visualization and comparison of results.

Digital data were collected from a variety of public sources (e.g., Kepner et al., 2003). The year 2000 was used as baseline condition and a set of land-cover/land-use maps were developed for the year 2020 based on current land management and projected census growth (Steinitz et al., 2003). For the purpose of this study, the 2020 maps were selected for three scenarios which reflected important contradictions in desired future policy based on stakeholder input. The scenarios are listed in Table I and basically reflect changes in population within the watershed, patterns of growth, and development practices and constraints. The Constrained Scenario is the most conservation oriented, the Plans Scenario reflects the most likely census predictions with zoning options designed to

Table I. Scenarios for future urbanization of the Upper San Pedro River Basin in the year 2020.

CONSTRAINED	Assumes lower population (78,500 inhabitants) than presently forecast for 2020. Development is concentrated in mostly existing developed areas (i.e., 90% urban). Removes all irrigated agriculture within the river basin.
PLANS	Assumes population increase as forecast for 2020 (95,000 inhabitants). Development is in mostly existing developed areas (i.e., 80% urban and 15% suburban). Removes irrigated agriculture within a 1-mile buffer zone of the river.
OPEN	Assumes population increase is more than the current 2020 forecast (111,500 inhabitants). Most constraints on land development are removed. Development occurs mostly into rural areas (60%) and less in existing urban areas (15%). Irrigated agriculture remains unchanged from current policy except for prohibiting new expansion near the river.

accommodate growth, and the Open Scenario is the least conservation and most development positioned option. It also assumes a greater than predicted population with few constraints on land development.

Our modeling approach involved running SWAT using the 2000 baseline land cover to parameterize the model to determine reference condition. SWAT was run using 12 years of continuous daily rainfall and temperature data (1960–1972) from a single gauge in the center of the basin. The watershed was discretized with a contributing source area of 9,200 ha, producing 67 sub-watershed elements (Figures 2–5). The same simulation was performed using each of the three 2020 land-cover scenarios to develop parameter inputs. Average annual outputs from the three alternative futures were then differenced from the baseline values to compute percent change in average daily values over the 20-year period. It is important to note that the model was not calibrated, and in our following analysis of the results we have focused on the relative magnitude and spatial distribution of the computed changes.

3. Results

Surface runoff, channel discharge, percolation, and sediment yield were simulated using the SWAT model within AGWA for the three 2020 scenarios. Results from the simulation runs are given in Table II and Figures 2, 3, 4, and 5. The figures show the relative departure from the 2000 baseline year and illustrate the spatial variability of changes to the surface-water hydrology. In general, the simulation results indicate that land-cover changes associated with future development will significantly alter the hydrologic response of the watershed. Changes are primarily associated with increasing urbanization and the associated replacement of vegetated surfaces with impervious ones.

In the case of surface runoff the simulations show average increases over the 20-year period commensurate with increases in urbanization. There is considerable spatial variability of simulated hydrologic response. Although most sub-watershed elements exhibited an increase in runoff, other areas showed improvement or decreasing runoff (Figure 2). The greatest change was simulated for the Open Scenario with an average increase of 12,787 m^3/day over the 2000 baseline (Table II). Simulated increases in surface runoff predominantly occur within sub-watersheds distributed in the northern reaches of the watershed near Benson, Arizona.

Table II. Simulated average daily surface runoff, percolation, and sediment yield for the 2000 baseline conditions and predicted relative change for each of the three development scenarios. Baseline and predicted change in the daily groundwater overdraft (Steinitz et al., 2003) is shown for reference.

	Baseline 2000	Simulated Percent Relative Change 2000–2020		
		Constrained 2020	Plans 2020	Open 2020
Surface runoff (m^3/day)	186,538	4.3	3.7	6.9
Percolation (m^3/day)	42,760	-2.7	-3.0	-4.6
Sediment yield (t/day)	1,042	4.4	3.7	7.0
Groundwater overdraft (m^3/day)	131,494	-57.6	-42.1	8.1

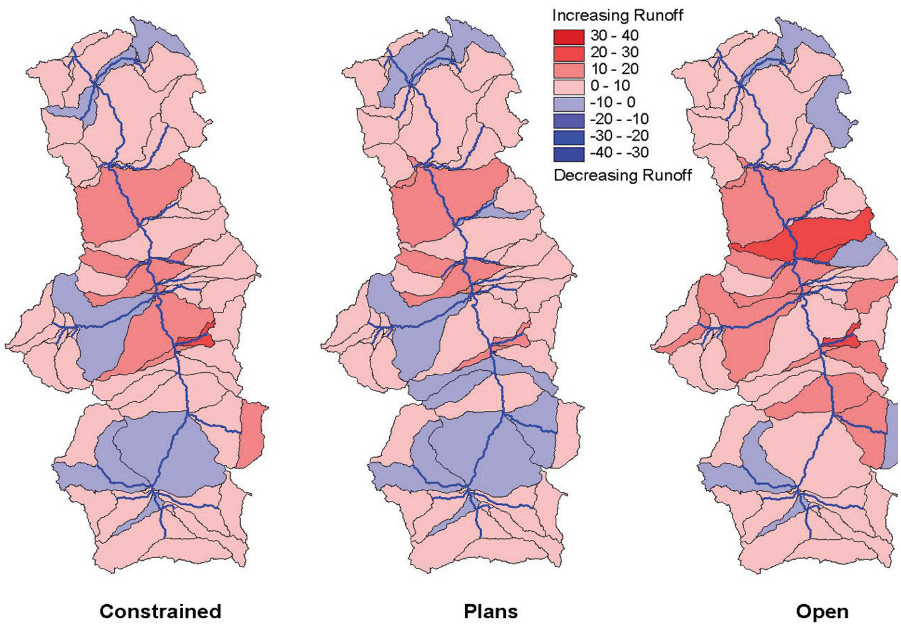

Figure 2. Percent change in surface runoff, 2000–2020, Upper San Pedro River Basin, Arizona/Sonora.

Percent change in simulated channel discharge agrees closely with results for surface runoff. Figure 3 shows change in simulated mean daily channel discharge relative to the 2000 baseline for each of the three development scenarios. By mapping this model output for each reach in the model area it is possible to visually identify reaches that are anticipated to experience the greatest changes in their hydrologic regime as a result of the land-cover/land-use change. Important changes in the magnitude and frequency of flooding increase the likelihood of channel scour and associated negative impacts on riparian vegetation. As such, the simulated changes to the hydrologic regime mapped in Figure 3 can also be viewed as an index of riparian vulnerability to the unmitigated future development. As in the previous example, channel discharge increased most under the Open Scenario and although the results are spatially variable, the greatest impact seems to be concentrated in the sub-watersheds in the northern portion of the San Pedro near Benson, Arizona where most new development is forecast.

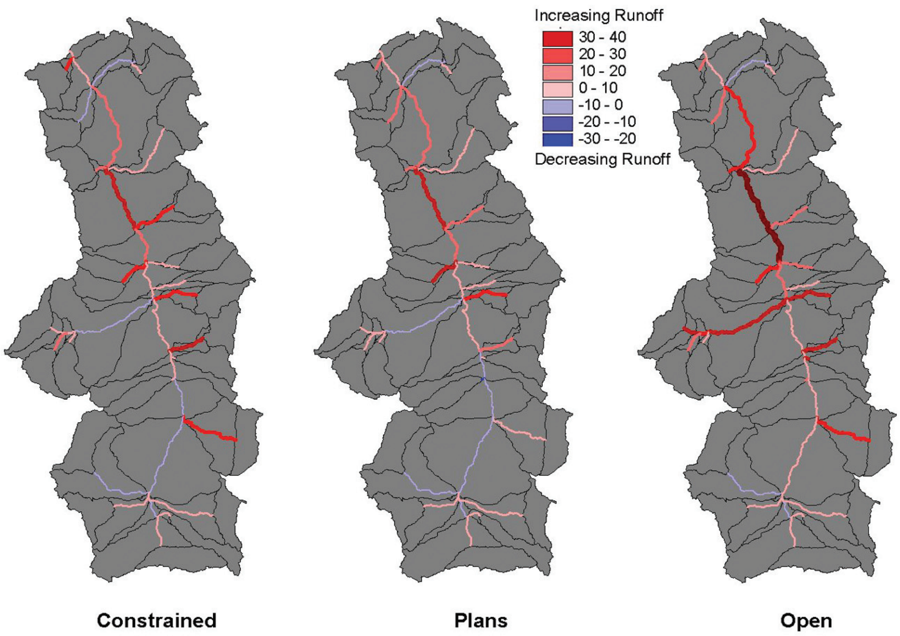

Figure 3. Percent change in channel discharge, 2000–2020, Upper San Pedro River Basin, Arizona/Sonora.

Sediment yield and erosion are directly related to runoff volume and velocity. The percent change in sediment yield simulated with SWAT also displayed a high degree of spatial variability across the basin and between the three scenarios (Figure 4). Sub-watersheds with the greatest increase in sediment yield did not necessarily correspond with those exhibiting the greatest change in surface runoff, however those model elements in the southern headwaters generally showed the least increase in both variables. Differences between the two outputs may also be reflected in the subtle nuances of soil type and texture variability across the sub-watersheds. It remains apparent, however, that under the most developed Open Scenario more sediment is expected to erode and be transported offsite than for the other two options.

Percolation is a hydrologic measure of the water volume that is able to infiltrate into the soil past the root zone to recharge the shallow and/or deep water aquifers. Figure 5 displays the simulated change in percolation for the three development scenarios. Although the model predicts some improvement in the watershed headwaters where human inhabitation is most dispersed, overall percolation is expected to decrease in all options as urban impervious surfaces are expanded, especially under the Open Scenario (Table II). The 2000 baseline estimates percolation at 42,760 m^3/day and that this amount will decrease by 1,986 m^3/day (4.6%) under the Open option. Most of the simulated decrease in this parameter was observed in the more northern sub-watersheds downstream from the incorporated city of Benson, Arizona.

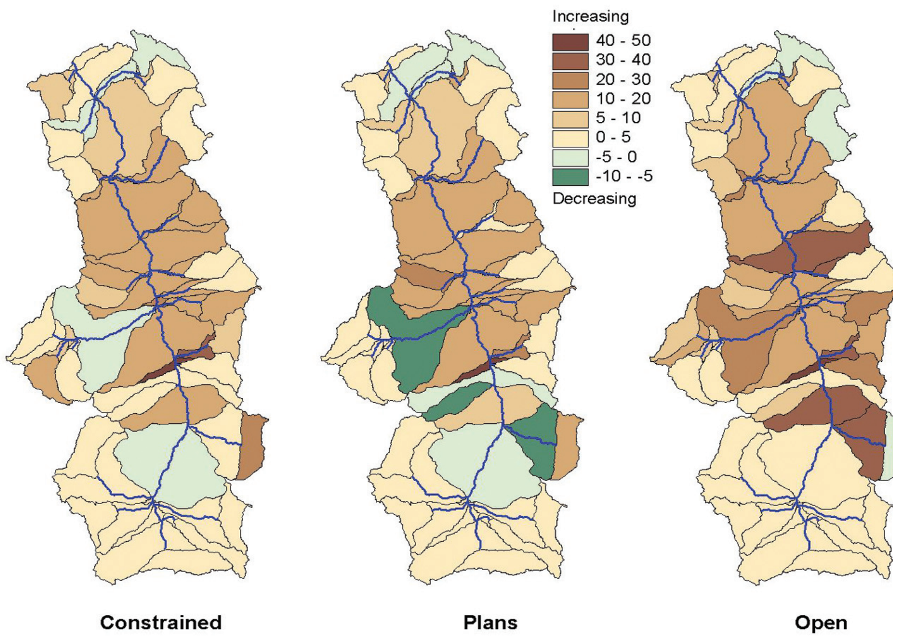

Figure 4. Percent change in sediment yield, 2000–2020, Upper San Pedro River Basin, Arizona/Sonora.

In general, under a future urbanizing environment the model simulation results appear to indicate that important impacts to the watershed hydrology can be expected. The most notable changes are likely to be increases in the amount of runoff, channel scour, and sediment discharge, and a loss of surface-water access to the groundwater table. This appears to agree with the results reported by Steinitz et al. (2003) who predicted changes in groundwater storage for the three 2020 scenarios (Table II). In that study the largest groundwater overdraft (10,608 m^3/day above the 2000 baseline) was predicted for the Open Scenario.

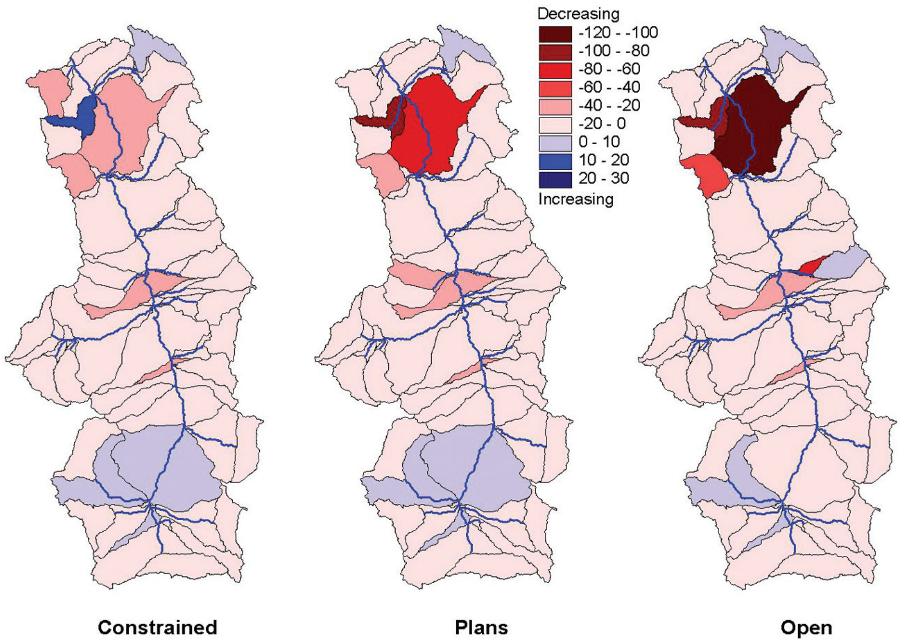

Figure 5. Percent change in percolation, 2000 –2020, Upper San Pedro River Basin, Arizona/ Sonora.

4. Summary and Conclusions

The hydrologic responses resulting from three development scenarios for the Upper San Pedro River Basin were evaluated using AGWA, a GIS tool developed to integrate landscape information with hydrological process models to assess watershed impacts. This differed from previous alternative futures research within the San Pedro watershed in that it examined the spatially-variable impact of land-cover/land-use change on the surface-water hydrologic regime. With this type of assessment it is possible to rapidly evaluate likely changes in surface runoff throughout a basin, as well as the cumulative downstream change as widely distributed tributary impacts are felt in the main channel. In this fashion, it is possible to assess the vulnerability of potentially sensitive areas to basin-wide development alternatives.

For the purpose of this study, negative impacts are considered to be any increase in surface runoff, channel discharge, sediment yield, and/or declines in groundwater percolation. The impacts are summarized graphically by percent change relative to the 2000 reference condition for each of the alternative futures using sub-watersheds as the comparative unit. Urbanization and irrigated agriculture are presumed to be the two major environmental stressors affecting watershed condition of the Upper San Pedro River Basin.

The hydrologic modeling results indicate that negative impacts are likely under all three of the future scenarios as a result of predicted urbanization, however there is remarkable variation in their specific hydrologic responses, particularly between the Constrained and Open Scenarios.

In general, the Open Scenario has the greatest negative impact on surface water hydrology and results in greater simulated surface runoff, channel discharge, and sediment yield than the other options, especially in the downstream reaches near Benson, Arizona. Additionally, percolation and thus groundwater recharge is most reduced under this option. This scenario favors development and allows for the largest future population increase within the watershed.

The Constrained and Plans alternative futures have the least negative impacts to the surface-water hydrology. These options are less attractive to developers in that they direct most future development into existing developed areas and minimally allow only 10% and 20%, respectively, of new residents to distribute outside of the urban areas (Table I).

Areas within the watershed are valued both for development and for conservation purposes and this sometimes brings human values into direct conflict. Clearly policy decisions regarding both population growth (particularly in Arizona) and irrigated agriculture will have important impact on future water use and conservation.

Although the findings in this study were not completely unexpected the authors believe that scenario analysis can help better understand and visualize how today's decisions regarding conservation and development act together to change the future. It should be pointed out, however, that careful calibration of any model is necessary before quantitative evaluations are made. The present study endeavors to demonstrate the general potential of integrating spatial data and distributed modeling in natural resource management. The combination of both landscape analysis with hydrological modeling can be widely applied on a variety of landscapes, watersheds, and regions and provides an important tool to assess vulnerability. The use of scenarios thus allows stakeholders and decision-makers to assess the relative impacts of several alternative sets of options and thus provides an important tool to help make better informed choices for an improved future.

References

Arnold, J.G., Williams, J.R., Srinivasan, R., King, K.W. and Griggs, R.H.: 1994, 'SWAT: Soil Water Assessment Tool', U. S. Department of Agriculture, Agricultural Research Service, Grassland, Soil and Water Research Laboratory, Temple, TX, USA.

CEC: 1998, 'Advisory Panel Report on the Upper San Pedro River Initiative: Recommendations and Findings presented to the Commission for Environmental Cooperation', Commission for Environmental Cooperation, Montreal, Canada.

Ebert, D.W. and Wade, T.G.: 2000, *Analytical tools interface for landscape assessments (ATtILA) User Guide Version 2.0*, U.S. Environmental Protection Agency, Office of Research and Development, Las Vegas, NV, USA.

ESRI: 2001, *ArcView Version 3.2a Software and User Manual*, Environmental Systems Research Institute, Redlands, CA, USA.

Hernandez, M., Kepner, W.G., Semmans, D.J., Ebert, D.W., Goodrich, D.C. and Miller S.N.: 2003, 'Integrating a Landscape/Hydrologic Analysis for Watershed Assessment,' in K.G. Renard, S.A. McElroy, W.J. Gburek, E.H.Canfield and R.L. Scott (eds.), *Proceedings of the First Interagency Conference on Research in the Watersheds,* Agricultural Research Service, Benson, AZ, USA, pp. 461-466.

Houghton, R.A., Hobbie, J.E., Melillo, J.M., Moore, B., Peterson, G.J., Shaver, G.R. and Woodwell, G.M.: 1983, 'Changes in the carbon content of terrestrial biota and soil between 1860 and 1980: a net release of CO_2 to the atmosphere', *Ecol. Monogr.* **53**, 235–262.

Kepner, W.G., Semmens, D.J., Heggem, D.T., Evanson, E.J., Edmonds, C.M., Scott, S.N. and Ebert, D.W.: 2003, *The San Pedro River Geo-Data Browser and Assessment Tools.* CD-ROM *(EPA/600/C-03/008* and *ARS/152432),* U.S. Environmental Protection Agency, Office of Research and Development, Las Vegas, NV, USA; U.S. Department of Agriculture, Agricultural Research Service, Tucson, AZ, USA.

Kepner, W.G., Watts, C.J., Edmonds, C.M., Maingi, J.K., Marsh, S.E. and Luna, G.: 2000, 'A landscape approach for detecting and evaluating change in a semi-arid environment', *Environ. Monit. Assess.* **64**, 179–195.

Kepner, W.G., Edmonds, C.M. and Watts, C.J.: 2002, 'Remote Sensing and Geographic Information Systems for Decision Analysis in Public Resource Administration: A Case Study of 25 Years of Landscape Change in a Southwestern Watershed', *EPA/600/R-12/039*, U.S. Environmental Protection Agency, Office of Research and Development, Las Vegas, NV, USA, p. 23.

Lahlou, M., Shoemaker, L., Choudry, S., Elmer, R., Hu, A., Manguerra, H. and Parker, A.: 1998, 'Better assessment science integrating point and nonpoint sources: BASINS 2.0 User's Manual', *EPA-823-B-98-006,* U.S. Environmental Protection Agency, Office of Water, Washington, DC, USA.

Miller, S.N., Semmens, D.J., Miller, R.C., Hernandez, M., Goodrich, D.C., Miller, W.P., Kepner, W.G. and Ebert, D.: 2002, 'GIS-based Hydrologic Modeling: The Automated Geospatial Watershed Assessment Tool', *Proceedings of the 2nd Federal Interagency Hydrologic Modeling Conference*, Las Vegas, NV, USA, p. 12.

McDonnell, M.J. and Pickett, S.T.A. (eds.): 1993, *Humans as Components of Ecosystems*, Springer-Verlag, New York, NY, USA.

Schwartz, P.: 1996, *The art of the long view: paths to strategic insight for yourself and your company*, Currency Doubleday, New York, NY, USA, p. 272.

Smith, R.E., Goodrich, D.C., Woolhiser, D.A. and Unkrich, C.L.: 1995, 'KINEROS – A kinematic runoff and erosion model', in V.P. Singh (ed.), *Computer Models of Watershed Hydrology*, Water Resources Publications, Highlands Ranch, CO, USA, p.1130.

Steinitz, C.: 1990, 'A framework for the theory applicable to the education of landscape architects (and other environmental design professionals)', *Landscape Journal.* **9** (2), 136–143.

Steinitz, C.: 1993, 'A framework for theory and practice in landscape planning', *GIS Europe.* July (1993), 42–45.

Steinitz, C., Binford, M., Cote, P., Edwards, T. Jr., Ervin, S., Forman, R.T.T., Johnson, C., Kiester, R., Mouat, D., Olson, D., Shearer, A., Toth, R. and Wills, R.: 1996, 'Biodiversity and Landscape Planning: Alternative Futures for the Region of Camp Pendleton California', Graduate School of Design, Harvard University for the Biodiversity Research Consortium, Cambridge, MA, USA, p. 142.

Steinitz, C., Anderson, R., Arias, H., Bassett, S., Cablk, M., Flaxman, M., Goode, T., Lozar, R., Maddock, T., Mouat, D., Rose, W., Peiser, R. and Shearer, A.: 2000, 'Summary Report: Alternative Futures for the Upper San Pedro River Basin Arizona, U.S.A. and Sonora, Mexico', Harvard University, Graduate School of Design, Cambridge, MA, USA, p. 19.

Steinitz, C., Arias, H., Bassett, S., Flaxman, M., Goode, T., Maddock T. III, Mouat, D., Peiser, R. and Shearer, A.: 2003, *Alternative Futures for Changing Landscapes. The Upper San Pedro River Basin in Arizona and Sonora*, Island Press, Washington, DC, USA.

Tellman, B., Yarde, R. and Wallace, M.G.: 1997, 'Arizona's Changing Rivers: How People Have Affected the Rivers', *Water Resources Research Center Issue Paper 19*, University of Arizona, Tucson, AZ, USA.

Turner, B.L. (ed.): 1990, *The Earth as Transformed by Human Action*, Cambridge University Press with Clark University, Cambridge, MA, USA.

USEPA: 2000, 'Environmental Planning for Communities. A Guide to the Environmental Visioning Process Utilizing a Geographic Information System (GIS)', *EPA/625/R-98/003*, U.S. Environmental Protection Agency, Office of Research and Development, Cincinnati, OH, USA, p. 49.